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Published in:
Geological Society of Denmark. Bulletin

Publication date:
2016

Document version
Publisher's PDF, also known as Version of record

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Petersen, T.G, Hamann, N.E. & Stemmerik, L. 2016. Correlation of the Palaeogene successions on the North-East Greenland and Barents Sea margins. ©2016 by Bulletin of the Geological Society of Denmark, Vol. 64, pp. 77–96. ISSN 2245-7070. (www.2dgf/publikationer/bulletin).

In this study we use seismic stratigraphy to link the Palaeogene succession of the North-East Greenland shelf with that of the more accurately dated Cenozoic succession on the partly conjugate Norwegian margin in the West Barents Sea. The margins show a comparable stacking of seismic facies and we propose that this symmetry reflects a genetic relationship between the conjugate plates. On both margins, the earliest deposition is constricted by highs inherited from Mesozoic rifting. On the North-East Greenland shelf, the Danmarkshavn Ridge forms a barrier, whereas the footwall uplift along the west margin of Veslemøy High constrains the deposition in the West Barents Sea area. Pronounced progradational events shifted the depocentres of both margins towards the central axis of breakup during the more tectonically active breakup phase. Deposition during the early drift stage is dominated by a relatively homogenous distribution of sediments across both margins and further basinward migration of the depocentres. Based on correlation of the seismic stratigraphic units, the Palaeogene succession of the North-East Greenland shelf is subdivided into pre-breakup deposits of early Paleocene age, syn-breakup deposits of latest Paleocene to early Eocene age and (early) drift deposits of late Eocene to Oligocene age.

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Received 15 June 2015
Accepted in revised form 25 June 2016
Published online 16 November 2016

Dating of seismic sequences represents a major challenge in stratigraphic and paleogeographic analyses, hydrocarbon exploration and resource assessment of sedimentary basins without well control (Gautier *et al.* 2009). The North-East Greenland shelf is one such 'white spot' where dating of the depositional basins and their infill is tentative and based on comparison to nearby outcrops and information from the better investigated Norwegian margin (Hamann *et al.* 2005). In North-East Greenland, only the youngest of the pre-Quaternary sediments have been drilled by ODP well 913 that reaches down into the Eocene, and seismic correlation to this borehole provides firm dating of the youngest seismic units on the oceanic crust (Berger & Jokat 2008). The location of the seismic and well data is presented in Fig. 1.

In this paper we discuss and test the potential of using age data from the conjugate Norwegian margin to improve dating of the Palaeogene succession on the North-East Greenland shelf since outcrop data from East and North Greenland are sparse (Hamann *et al.* 2005). The Palaeogene succession offshore North-East Greenland was recently described and linked to the breakup of the northern North Atlantic by dividing it into seismic units dated as pre- and syn-breakup and early drift in age (Petersen *et al.* 2015). The succession records the opening of the northern North Atlantic, so a more precise dating of the seismic units could help to better understand the evolution of the North-East Greenland shelf compared to the Norwegian margin.

The comparison between the Greenland and Norwegian margins is somewhat challenged by the complexity of the opening between North-East Greenland and the Barents Shelf and the timing of the shift from strike-slip motion to seafloor spreading in the De Geer Mega Shear zone (Figs 2, 3) (Voss & Jokat 2009). The conjugate margin to the southern Danmarkshavn and Thetis basins is the Lofoten-Vesterålen-Senja segment of the Norwegian margin, whereas the western Barents Sea margin including the Sørvestsnaget Basin and Veslemøy High is conjugate to the northern part of the North-East Greenland shelf, including the northern

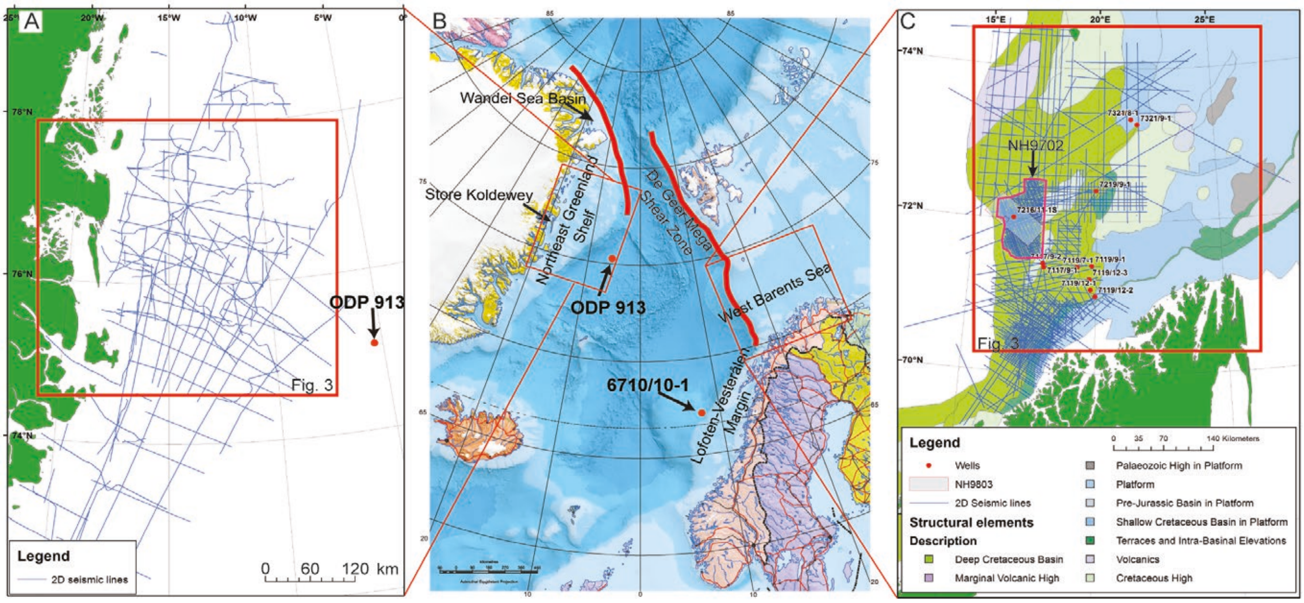

Fig. 1. **A**: Seismic data available for this study of the North-East Greenland margin. **B**: Overview of the North Atlantic region. The two black frames show the locations of maps A and C; the thick red lines are the De Geer Mega Shear Zone. North-East Greenland Map modified from http://atlas.gc.ca/. **C**: Seismic data and wells on the Barents Shelf (Modified from www.npd.no).

Danmarkshavn and Wandel Sea basins (Fig. 2) (e.g. Tsikalas *et al.* 2001).

The temporal and spatial resolution of the spreading history of the northern North Atlantic is well documented by magnetic anomalies in the oceanic crust (Talwani & Eldholm 1977; Tsikalas *et al.* 2008; Gaina *et al.* 2009; Ogg 2012). Spreading in the Norwegian-Greenland Sea started at *c.* 55 Ma (Chron C25) (Fig. 2a) (Ziegler & Cloetingh 2004). Several changes of spreading direction and speed occurred during the early opening history, most prominently during the Eurekan Orogeny between 49 and 47 Ma (Chron C22n–C21n, based on the magnetostratigraphy of Ogg 2012) when the spreading rates between Eurasia and Laurentia slowed down significantly as a result of compression in the Canadian Arctic Islands (Fig. 2C). The onset of opposite absolute plate motion started at *c.* 33 Ma (Chron C12r), and at 25 Ma (Chron C7r) full separation was achieved along most of the newly formed continental margins (Gaina *et al.* 2009; Døssing *et al.* 2010) (Fig. 2C). The orientation of the De Geer Mega Shear zone relative to plate motion directions caused differences in the tectonic regimes along the Norwegian Sea, West Barents Sea and North-East Greenland conjugate margins (Breivik *et al.* 1998; Olesen *et al.* 2007). Extension dominated along the North-East Greenland and Norwegian Sea margins; the northern Wandel Sea segment of the North-East Greenland margin was dominated by complex strike-slip tectonics (Døssing *et al.* 2010), and compression prevailed in Spitsbergen (Dore 1991; Bergh & Grogan 2003; Bruhn & Steel 2003; Ryseth *et al.* 2003; Gernigon *et al.* 2009).

The Palaeogene succession on the North-East Greenland shelf is characterized by unique depositional geometries shifting from low angle clinoformal packages in basinal lows to progradational packages of steep clinoforms and finally successions with sub-horizontal geometries (Petersen *et al.* 2015). The shift in depositional geometries has been interpreted in a rift to drift margin context to reflect the ongoing opening of the northern North Atlantic (Petersen *et al.* 2015).

Setting

The North-East Greenland shelf covers the area from *c.* 70°N to 82°N along the East Greenland coast and is up to 500 km wide (Fig. 1). The shelf is dominated by N–S to NNE–SSW oriented structural highs and basins formed during prolonged late Palaeozoic and Mesozoic rifting (Hamann *et al.* 2005). The most prominent structural elements are the Koldeway Platform, the Danmarkshavn Basin, the Danmarkshavn Ridge, and the Thetis Basin at the outer edge of the shelf (Fig. 3) (Hamann *et al.*, 2005). The Palaeogene succession is up to *c.* 850 milliseconds (ms) (in the order of 800–1000 m) thick and unconformably overlies the N–S trending Mesozoic and Palaeozoic structural elements. Evidence of Cenozoic volcanism is mostly absent on the northern part of the shelf, whereas both intrusives and extrusives are common both onshore and offshore south of *c.* 75°N (Brooks 2011; Petersen *et al.* 2015).

The only well penetrating Palaeogene deposits offshore North-East Greenland is ODP Site 913 on the oceanic crust at 75°29'N, 06°96'W (Fig. 1B). It was used by Berger and Jokat (2008) to subdivide the Cenozoic succession into a pre-mid-Miocene GB-1 and a post-mid-Miocene GB-2 unit. However, the locality of this well is not ideal for seismic correlation with the succession in the Danmarkshavn Basin. Scattered Tertiary outcrops in North and North-East Greenland have all been attributed to the Paleocene–Lower Eocene (Lyck & Stemmerik 2000; Nøhr-Hansen *et al.* 2011).

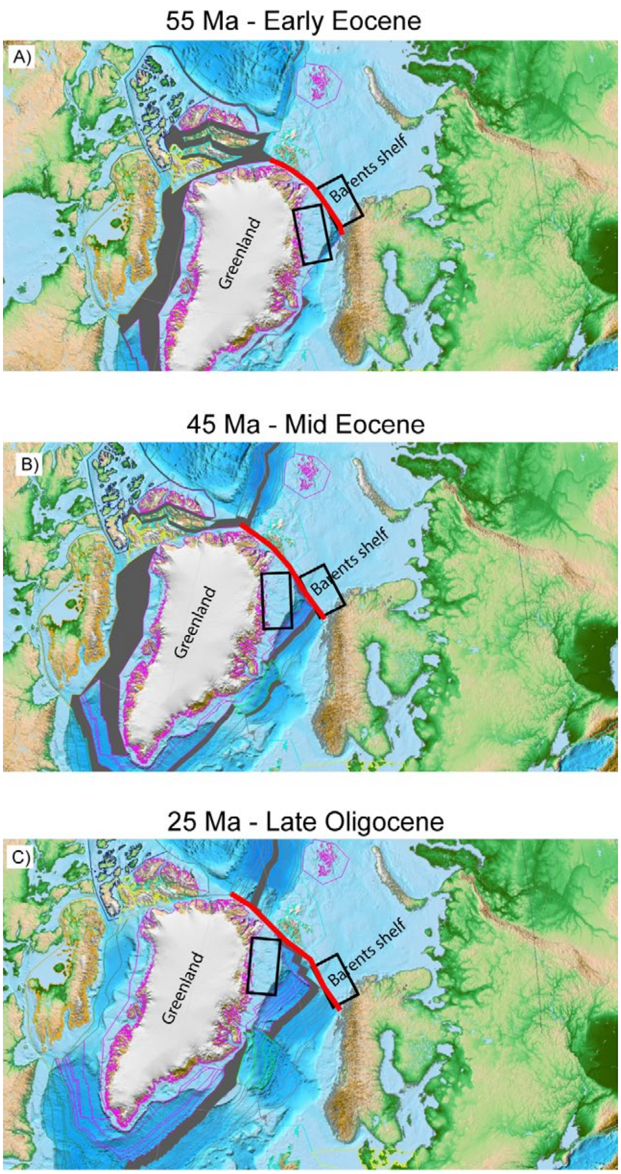

Fig. 2. Plate tectonic reconstruction of Greenland and Eurasia. **A**: Initial geometry prior to the opening. **B**: Eurekan orogeny where compression in the Canadian Arctic Islands can be seen, as well as compression at the west coast of Svalbard. **C**: Complete breakup along most of the margins, except for the Wandel Sea area (Reconstruction based on Gplates: www.gplates.org). Thick red lines are the De Geer Mega Shear Zone.

The North-East Greenland shelf is the conjugate margin to the West Barents Sea margin in the north and northeast and the Lofoten-Vesterålen margin to the east and southeast. Although part of the same conjugate margin system, the Lofoten-Vesterålen margin is tectonically very different from the West Barents Sea margin, since it was dominated by extensional deformation during the continental breakup, whereas the Barents Sea margin was dominated by transtensional deformation (Tsikalas *et al.* 2001; Gaina *et al.* 2009). Potential field data have been used to identify transverse lineaments segmenting the Lofoten-Vesterålen margin and correlation to North-East Greenland has been suggested (Tsikalas *et al.* 2005), although the lineaments have been disputed and seen as artefacts caused by poor data quality (Olesen *et al.* 2007). In the current study, no evidence of hard linked transforms has been identified in the seismic data on the North-East Greenland shelf. Faerseth (2012) has described an E–W accommodation zone at 68°30'N offshore Norway, acting as a right-lateral, soft-linked transfer zone across which the dips and strikes of the faults change orientation. On the North-East Greenland shelf, right-lateral offset of the two segments of the Danmarkshavn Ridge is seen in map view (Fig. 3). There is no evidence of transform faulting separating the two segments of the ridge, consistent with a soft-linked transform. The transfer zone on the North-East Greenland shelf aligns with the accommodation zone of Faerseth (2012) when reconstructing the plates to a pre/syn-breakup position.

On the Barents Sea shelf, Palaeogene sediments are limited to the western margin which covers the area from Spitsbergen in the north to the Norwegian Finnmark coast in the south and extends from 15°E to 25°E (Fig. 1). The continental to oceanic transition zone is named from south to north: The Senja Fracture Zone which consists of a sheared margin, the Vestbakken Volcanic Province associated with pull-apart tectonics, and the Hornsund Fault Zone (Fig. 3) (Faleide *et al.* 1996). From east to west, the most prominent structural elements in the West Barents Sea area are the Hammerfest and Bjørnøya Basins which are separated by the Loppa High in the east, and the Harstad, Tromsø and Sørvestsnaget Basins at the continental margin west of 20°E. The Senja Ridge and its elongation into the Veslemøy High subdivide the Sørvestsnaget Basin from the Tromsø Basin in the east (Fig. 3) (Knutsen & Vorren 1991). The Loppa High forms the eastern boundary of the Palaeogene deposits due to deepening of the erosional incision towards the east (Gernigon & Brönner 2012). Evidence of significant volcanism is seen in the Vestbakken Volcanic Province, a deep pull-apart basin created due to transtensional tectonics along the de Geer zone during the breakup at *c.* 51 Ma (Chron C23) (Tsikalas *et al.* 2002).

Several seismic stratigraphic schemes have been proposed for the Palaeogene deposits in the western Barents Sea (Table 1). Vorren (1991) was the first to establish a seismic stratigraphic framework based on mapping of three units in the Hammerfest Basin and five units in an area roughly corresponding to the Sørvestsnaget Basin and the southern Vestbakken Volcanic Province. Later, Faleide *et al.* (1993) refined the stratigraphy based on new seismic data, and further refinements of the seismic stratigraphy and better correlation between the basins were presented by Fiedler & Faleide (1996) and Ryseth *et al.* (2003) (Table 1), including correlation to well 7216/11-1s in the Sørvestsnaget Basin (Ryseth *et al.* 2003). The relatively complete succession of Palaeogene strata exposed in the Central Basin onshore Spitsbergen (Svalbard) forms a transgressive-regressive succession of fluvio-deltaic and marine sandstones and offshore shales deposited in a foreland basin which developed during the evolution of the West Spitsbergen Fold Belt (Bruhn & Steel 2003)

The foreland basin was initially, during the Paleocene, sourced from the east but later the drainage pattern changed and during the Eocene the source area was the evolving West Spitsbergen Fold Belt to the west (e.g. Bruhn and Steel, 2003; Petersen *et al.* 2016). The evolution of the Central Basin thus differs from the strike-slip dominated Sørvagnet Basin and Vestbakken Volcanic Province, adding to the complexity of the breakup history along the Barents Sea margin.

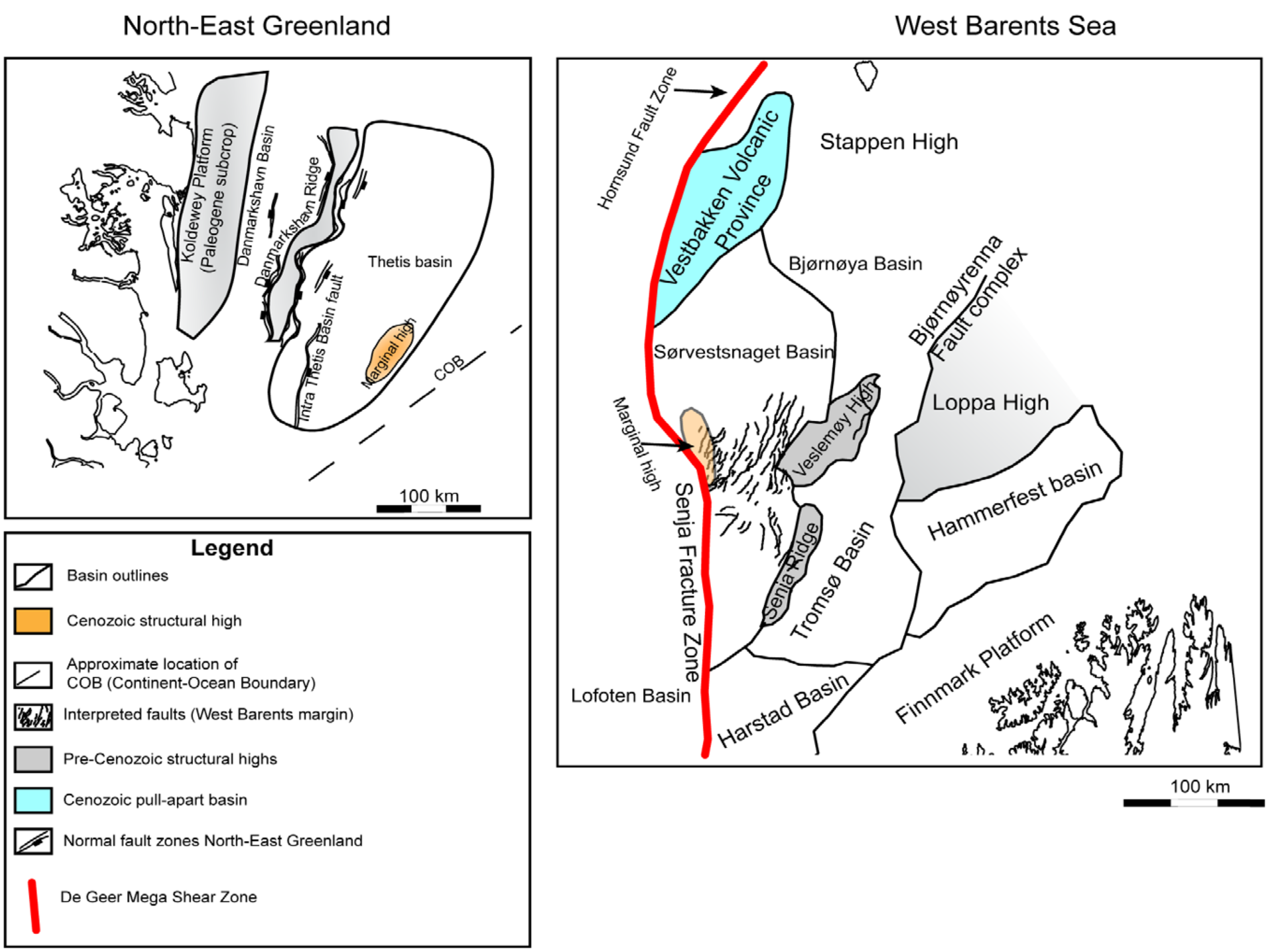

Fig. 3. Maps showing the main structural elements of the North-East Greenland shelf and the West Barents Sea. For location see Fig. 1. The North-East Greenland margin is dominated by NNE–SSW trending highs and lows, from west to east named Koldewey Platform, Danmarkshavn Basin, Danmarkshavn Ridge and Thetis Basin. The West Barents Sea margin includes the Lofoten Basin, Vestbakken Volcanic Province, Sørvestsnaget Basin, Veslemøy High and Senja Ridge lineament and the Trømsø Basin. The Palaeogene succession is absent due to erosion further east across the Loppa High. The De Geer Mega Sheer Zone includes several fault zones.

Table 1.1. Overview of the seismic stratigraphic sub-divisions of the Paleocene to Miocene succession in the West Barents Sea shelf area.

Vorren 1991		Faleide *et al*. 1993		Fiedler & Faleide 1996		Ryseth *et al*. 2003		This study	
Sub-division	Comments	Subdivision	Comments	Sub-division	Comments	Subdivision	Comments	Subdivision	Comments
ThB/TeB	Intra Miocene (15.5 Ma)					Base Miocene		Oligocene(?)	
								Near top Eocene	
				Te1-Te4		Intra Middle Eocene	Central Sørvestsnaget Basin	Mid Eocene seismic horizon	Unit top ages
ThA/TeA	Intra Eocene (50 Ma)							Lower Eocene seismic horison	
		BE	Base Eocene			Near top Paleocene		Paleocene seismic horizon 2	
					Base at 55 Ma			Paleocene seismic horizon 1	
		BT	Base Cenozoic			Near top Cretaceous		Base Cenozoic	

North-East Greenland margin

The continental breakup in the North Atlantic was associated with volcanism onshore East Greenland, and seismic observations reveal that the sedimentary succession on the East Greenland shelf south of *c.* 75°N is heavily intruded by volcanic rocks (Brooks 2011; Larsen *et al.* 2014). The East Greenland volcanics form part of the North Atlantic Large Igneous Province (NALIP) that covers substantial areas of the North Atlantic margin from the Rockall Plateau to the Vøring Margin on the Eurasian side, and the entire East Greenland margin south of *c.* 75° N (Brooks 2011; Larsen *et al.* 2014). The NALIP formed as a response to the opening of the North Atlantic and was emplaced between 64 Ma to 25 Ma with a distinct peak in the earliest Eocene, corresponding to the time of continental breakup (Brooks 2011; Larsen *et al.* 2014). The heating associated with the volcanism may have caused the observed uplift of the East Greenland margin, and from the seismic data it is evident that the North-East Greenland margin was most heavily eroded in the south where the intrusions are the most frequent (Petersen *et al.* 2015). This is also consistent with observations further south in East Greenland where the C5 event of Japsen *et al.* (2014) records early Eocene thermal uplift.

The stratal geometry of six seismic units in the Palaeogene succession along the inner, western part of the North-East Greenland shelf and three units in the eastern part of the shelf is believed to reflect the volcanic uplift history, and has facilitated a division into the pre-, syn- and post-volcanic successions described in details by Petersen *et al.* (2015) and summarized below and in Fig. 4. The data set used for these studies is part of in the NEG08 and KANUMAS surveys of the North-East Greenland shelf.

Pre-breakup succession

On the North-East Greenland shelf the Palaeogene succession rests unconformably on deeply eroded Mesozoic deposits (Hamann *et al.* 2005; Petersen *et al.* 2015). Initially, deposition was constrained to the Danmarkshavn Basin by the Danmarkshavn Ridge, which apparently acted as a positive element prior to and during the breakup. Low angle, eastward prograding clinoforms and a stacked mound complex infill the structural lows of the Danmarkshavn Basin (marked in yellow in Fig. 4A), and are overlain by sediments with plane parallel, low amplitude bedding (Petersen *et al.* 2015). The pre-breakup succession (yellow interval in Fig. 4) represents initial progradation into the basin, and isochrone maps show that the succession is constrained to the Danmarkshavn Basin by the Danmarkshavn Ridge (Fig. 5). The observed low-angle clinoforms and the mounded structures are consistent with deposition in a tectonically relatively quiet period with low source-to-sink relief of the depositional system. It is therefore interpreted as pre-dating the main volcanic event and the thermal uplift that may have occurred during continental breakup (Brooks 2011; Larsen *et al.* 2014). The main volcanic event occurred in the earliest Eocene, meaning that the pre-breakup unit is Paleocene in age (Larsen *et al.* 2014).

There is evidence of channel incision along the western edge of the Danmarkshavn Basin implying lowering of the base level during or after deposition. The cause of this incision is not well understood, but a possible explanation could be a sea level drop at the Cretaceous/Palaeogene interface (Miller *et al.* 2005).

Syn-breakup succession

In the Danmarkshavn Basin, the overlying succession (blue interval in Fig. 4) is dominated by clinoform packages prograding across the basin from the southwest to the northeast. The proximal part of the succession consists of relatively high angle clinoforms, and based on their steepness it is suggested that they contain the coarsest facies of the Palaeogene succession and represent a pronounced regression. The upper boundary of the syn-breakup interval is erosive towards the west which is believed to reflect the depositional response to regional uplift associated with the volcanism (Petersen *et al.* 2015). During this time interval, the main axis of sediment transport as defined by the location of depocentres and presence of clinoforms was shifted southwards from a position directly east of Store Koldewey to a position *c.* 100 km farther to the south (Fig. 5).

During the breakup phase, volcanism onshore and offshore most likely caused an increasing amount of uplift and erosion towards the south in the Danmarkshavn Basin, observed as truncation of reflectors at the upper boundary of the syn-breakup unit (see top of

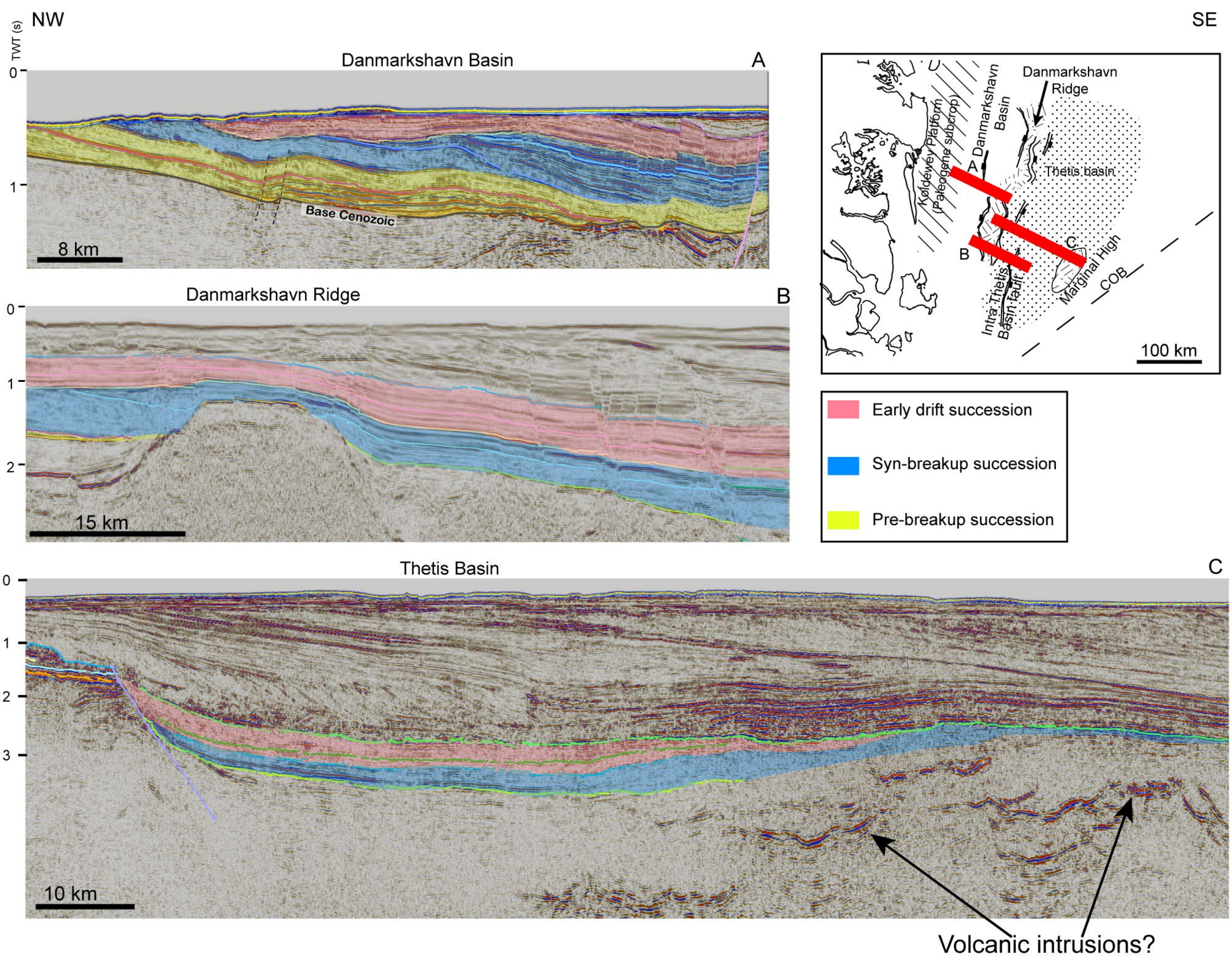

Fig. 4. Three seismic sections showing the geometry of the pre-breakup, syn-breakup and early drift Palaeogene succession, **A**: in the Danmarkshavn basin, **B**: across the Danmarkshavn Ridge, and **C**: in the Thetis Basin. Note that the sections are not presented in a N–S order, but they represent a proximal to distal order.

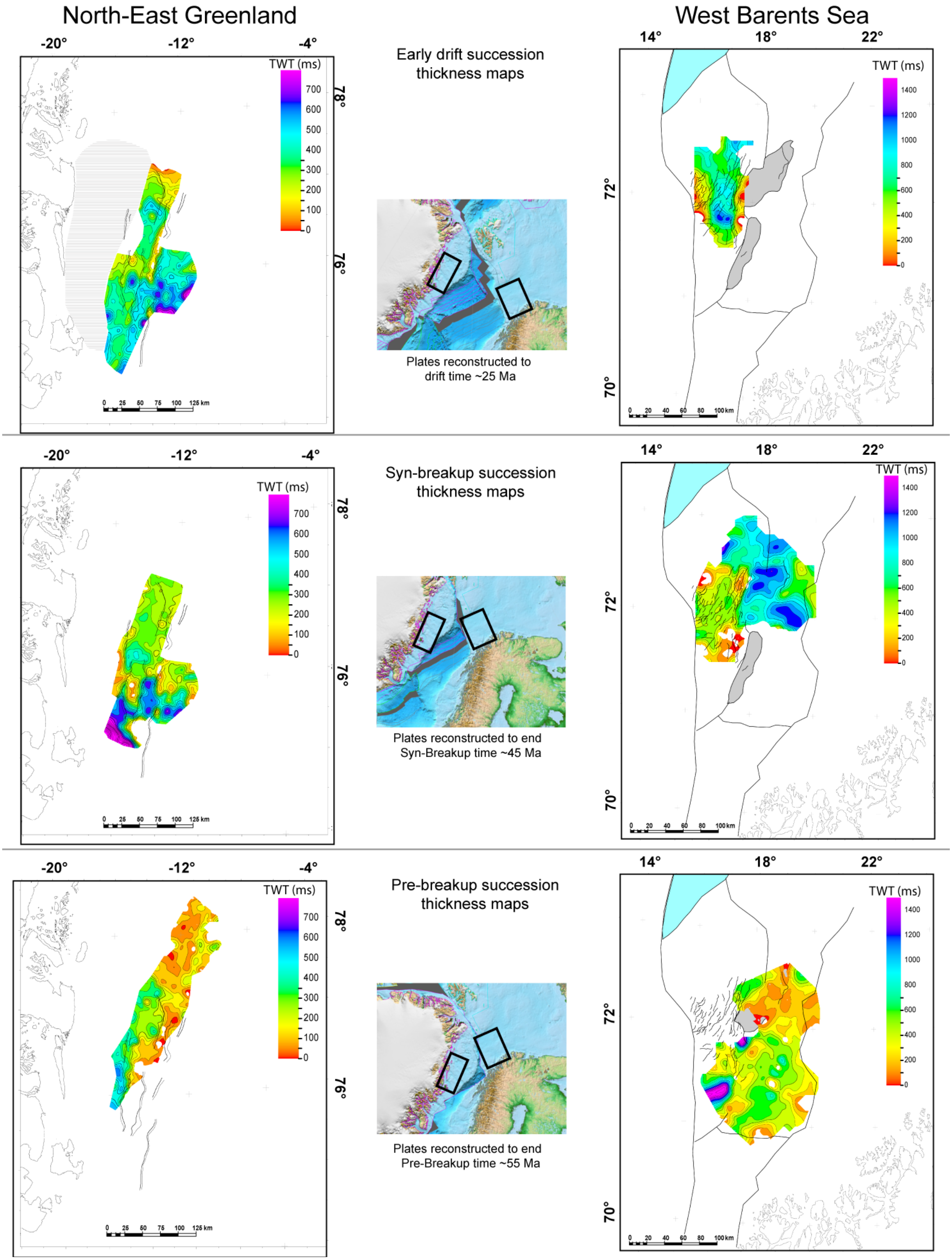

Fig. 5. Thickness maps as TWT maps showing locations of the main depocentres of pre-breakup, syn-breakup and early drift sediments with associated plate reconstructions representative for the plate geometries at the time of the deposition (plates reconstructed using Gplates: www. Gplates.org). A pronounced shift of depocentre towards the breakup axis is observed along both margins, which is a key observation for the correlation.

blue interval in Fig. 4A–B). This uplift caused a tilting of the margin towards the east to northeast, with associated erosion of mostly Paleocene deposits to the west and southwest, and increasing accommodation space in the more distally located Thetis Basin. There, the succession is characterised by plane parallel, low amplitude reflections, indicative of relatively homogenous sediments, potentially deposited in a sublittoral setting. Correlation between the Danmarkshavn Basin and the Thetis Basin is somewhat hampered by the Danmarkshavn Ridge, especially in the lower part of the succession (Petersen *et al.* 2015).

Early drift succession

The upper part of the Palaeogene succession (pink interval in Fig. 4) was deposited during a time interval dominated by large-scale subsidence across the North-East Greenland shelf which yielded a relatively constant thickness of the deposited succession across the shelf (Fig. 5; Petersen *et al.* 2015). Some increase in subsidence centrally in the Thetis basin is however recorded in the isochrone map of the early drift package (Fig. 4). The seismic data suggests that this increase in accommodation space is due to compaction of the thick Mesozoic succession of the Thetis Basin, since any faulting post-dates the deposition of the early drift succession (Fig. 5). Apparently, the Danmarkshavn Ridge no longer acted as a positive bathymetric element and deposition occurred in a low energy environment, most likely beneath wave base, based on the dominance of seismic facies characterised by sub-parallel internal reflections. Little or no evidence of tectonics are observed during this stage of the basin evolution, and the succession is attributed to a drift setting post-dating continental breakup.

West Barents Sea Margin

The geological evolution of the Western Barents Sea is relatively well documented (Knutsen & Larsen 1997; Ryseth *et al.* 2003; Geissler & Jokat 2004; Tsikalas *et al.* 2008). Palaeogene deposits are only preserved in a narrow zone along the margin of Eurasia consisting of the Vestbakken Volcanic Province, the Sørvestsnaget Basin, the Veslemøy High, the Senja Ridge, the Tromsø Basin and the Harstad Basin (Fig. 3) as they are eroded away further to the east as the result of Neogene incision. The succession is included in the Torsk Formation, Sotbakken Group, and is interpreted as dominated by marine, sublittoral to outer shelf claystones with rare deep-marine sandprone turbidites in the Sørvestsnaget Basin (Dalland *et al.* 1988; Ryseth *et al.* 2003). The sediments infilling the Western Barents Sea margin were derived from the eastern Barents Sea, where uplift and erosion of the underlying Palaeozoic–Mesozoic succession are widespread (Smelror & Basov 2009).

In this study, we focus on stratal geometries and their relation to the evolution of the margin during the Palaeogene breakup. The database consists of 2D seismic lines supplemented with 3D seismic and well data, and most seismic interpretations are based on the NH9702 2D and the NH9803 3D seismic surveys (Fig. 1C), (with support from additional vintage data sets). We have used public domain stratigraphic data from the Norwegian Petroleum Directorate (www.npd.no) to date the seismically defined units, and we have focussed on a number of key stratigraphic horizons, including the Base Paleocene, Top Paleocene, Early Eocene, Middle Eocene, and Base Neogene. Since our focus is on seismic units to be used for large-scale comparison with the North-East Greenland shelf, more detailed dating of the wells is not part of the current study.

The integration of seismic and well data allows us to distinguish six seismic units and thereby constrain shifts in deposition temporally. Correlation of the Palaeogene succession on the Loppa High, Senja Ridge and Sørvestsnaget Basin (Fig. 6) is based on information from the completion logs of wells 7117/9-1 and 7219/9-1, and data in Ryseth *et al.* (2003) for well 7216/11-1S.

Lower Paleocene seismic unit

The lower boundary is the Base Cenozoic seismic horizon and the top is Paleocene seismic horizon 1 (Fig. 7). The unit is restricted to fault-controlled lows along the western margin of the Loppa High and on the Veslemøy High (Fig. 7). It is not identified in the Sørvestsnaget Basin and is therefore only dated on the highs to the east. The Lower Paleocene seismic unit has been tied to well 7219/9-1, providing a base Paleocene age for the lower part and an early(?) Paleocene age for the upper part of the unit (Fig. 6).

The onset of Cenozoic sedimentation on the West Barents Sea Margin is recorded by low angle, subparallel seismic facies characteristic for the Lower Paleocene seismic unit. The Lower Paleocene deposits display an onlapping, lenticular internal architecture on the Veslemøy High. Footwall uplift along the western margin and of the high itself may have caused the Veslemøy High to be a positive structural element during the earliest Paleocene and it may have acted as a barrier for sediment input from the east. This assumption is based on the absence of the Lower Paleocene seismic unit in the Sørvestsnaget

Basin. Alternatively, lowermost Paleocene deposits are present in the Sørvestsnaget Basin, but are simply not recognised due to poor correlation across the fault zone separating the Sørvestsnaget Basin from the Veslemøy High.

The seismic facies suggests that the Lower Paleocene sediments were deposited in the distal part of a prograding system sourced from the east. This is in line with the pattern recognised in Spitsbergen and consistent with regional models (e.g. Smelror & Basov 2009; Petersen *et al.* 2016). The stratal geometries indicate deposition in a tectonically quiet period, and this is supported by the well log motifs which indicate a dominance of shaly sediments across the region throughout the Paleocene with a noticeable exception in the interval from *c.* 3500 to 3700 m MD (Measured Depth) in well 7216/11-1S where abundant tuffaceous fragments indicate vicinity to active volcanism (Fig. 6; Ryseth *et al.* 2003). Based on the stratal geometries and the dating of the succession, the Lower Paleocene seismic unit reflects deposition prior to breakup.

Paleocene seismic unit 2

The top of Paleocene seismic unit 2 is defined by Paleocene seismic horizon 2 (Fig. 7). Paleocene seismic unit 2 has a wider distribution than the underlying unit and reflects deposition sourced from the east and transgression of the highs east of the Sørvestsnaget Basin (Ryseth *et al.* 2003). It is tied to well 7219/9-1 with a suggested early (?) to end Paleocene age.

During this stage deposition became more widespread on the Veslemøy High, Loppa High and Tromsø Basin and was no longer constrained by fault blocks. The lower-to-upper Paleocene succession onlaps the rotated fault blocks on the Veslemøy High,

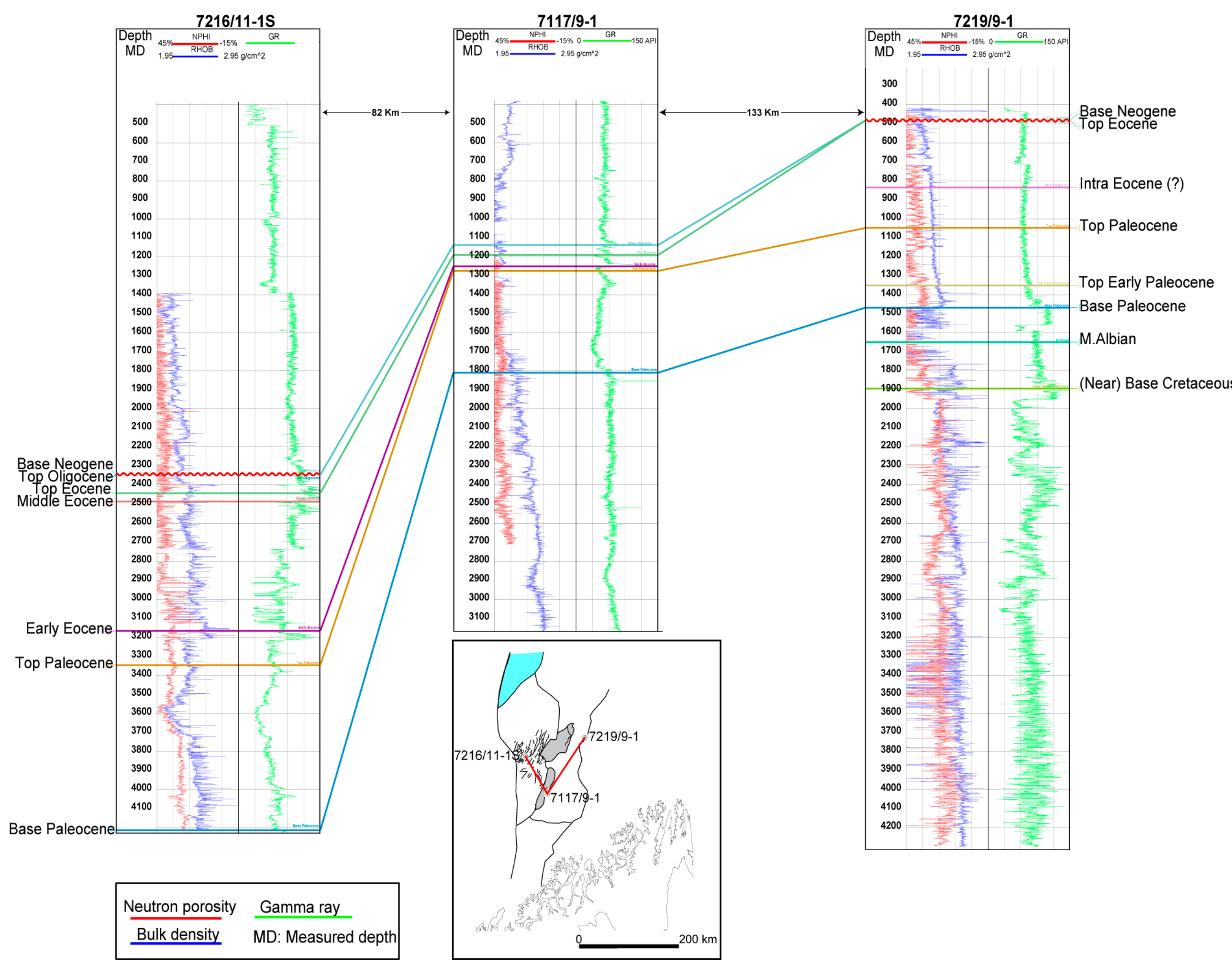

Fig. 6. Log correlation panel of wells 7219/9-1, 7117/9-1 and 7216/11-1S across the Loppa High, the Senja Ridge and the Sørvestsnaget Basin showing the Paleocene pre-breakup succession, the Eocene breakup package and the Oligocene early drift deposits. MD: Measured Depth in metres.

and maximum thickness is observed in the Tromsø Basin. Although the Paleocene seismic horizon 2 cannot be defined near the transition to the Sørvestsnaget Basin, it is clear that the seismic reflectors immediately above the Paleocene seismic horizon 1 display divergence from east to west toward the fault zone that separates the Veslemøy High from the Sørvestsnaget Basin in the west (Fig. 8), the Tertiary Hinge Line of Faleide (1988). This indicates that the West Barents Sea Margin underwent large wavelength subsidence prior to onset of the opening of the Norwegian-Greenland Sea in the earliest Eocene (Gaina *et al.* 2009; Gernigon *et al.* 2009).

The Paleocene seismic unit 2 is generally characterised by sub-parallel internal seismic facies indicating an aggradational rather than progradational stacking pattern, consistent with sedimentation in a sublittoral setting (Fig. 8) (Posamentier & Kolla 2003). Progradational stacking patterns are recognized in the Bjørnøyrenna area (Faleide *et al.* 1993), where well data indicate the presence of relatively sandprone facies. The amount of progradation increases during this period, but there is still no evidence of significant deepening of the basin, consistent with a pre-breakup age of the unit.

Lower Eocene seismic unit

The top of the Lower Eocene seismic unit is the lower Eocene seismic horizon (Figs 7, 8). The unit transgresses the Veslemøy High into the Sørvestsnaget Basin, with a large-scale reflection pattern that may suggest deposition in the distal part of a westwards prograding system. The thickness increases westwards into a depocentre localised over the fault zone that separates the Sørvestsnaget Basin and the Veslemøy High, making correlation between the two areas uncertain (Fig. 8). This indicates that significant accumulation of sediments occurred prior to the tectonic event that created the Sørvestsnaget Basin, as also indicated by the underlying lower-to-upper Paleocene succession. The Lower Eocene unit is tied to wells 7216/11-1S and 7219/9-1, suggesting a latest Paleocene to mid Eocene age for the succession (Ryseth *et al.* 2003).

Due to poor correlation across the fault zone, the actual timing of the subsidence east of the Tertiary Hinge Line on the Veslemøy High is not well constrained, but thickness variations across the rotated fault blocks in the Sørvestsnaget Basin indicate syntectonic deposition. The succession is erosionally truncated on the crest of the footwall block (Fig. 8) east of the fault zone separating the Sørvestsnaget and Vestbakken Volcanic Province Basins from the Veslemøy High and Stappen High areas (the Tertiary Hinge Line). The syn-depositional faulting and noticeable increase of progradation into the Sørvestsnaget Basin both point towards deposition during a time period with increased tectonic activity and uplift of the hinterland, and the Lower Eocene seismic unit is believed to reflect deposition during early breakup.

Middle Eocene seismic unit

The top of the middle Eocene seismic unit is the mid Eocene seismic horizon (Fig. 9). The unit is tied to well 7216/11-1 S according to Ryseth *et al.* (2003) (Fig. 6). The

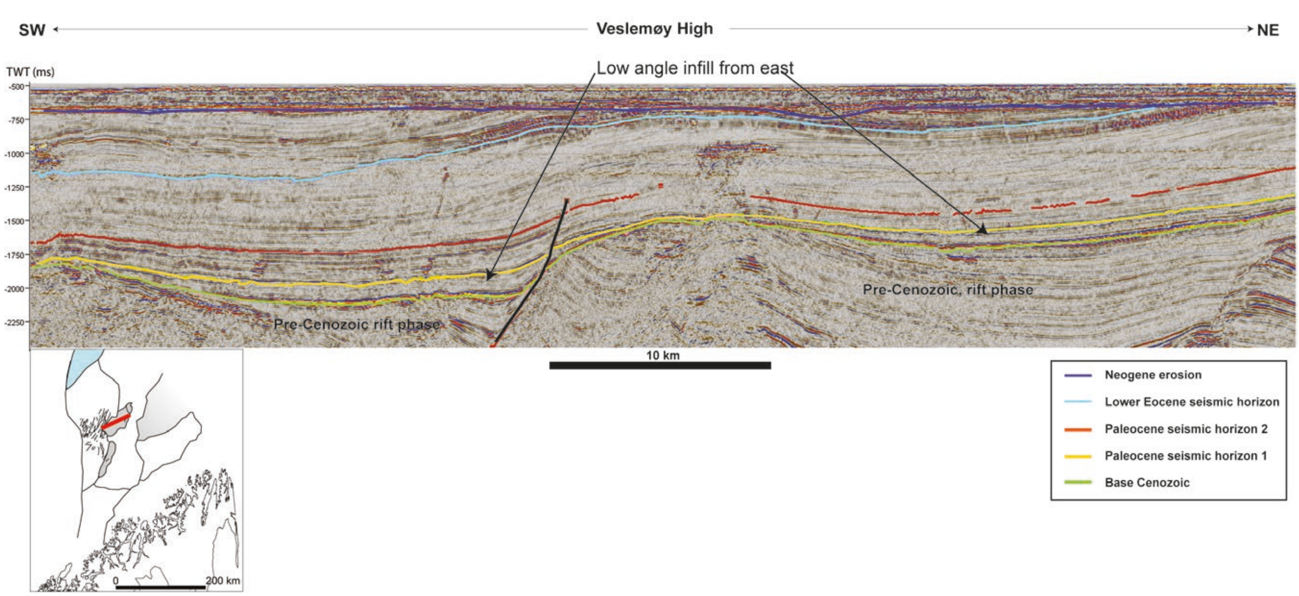

Fig. 7. Seismic section across the Veslemøy High (NH9702-234). Low angle infill dominates in the lows between the uplifted footwalls. For location of inset map see Fig. 1.

tie is robust, with reliable ages in the well and good quality 3D seismic data. The unit is only described in the Sørvestsnaget Basin due to erosion of the eastern margin of the basin or non-deposition.

The eastern extent of the middle Eocene succession onto the Veslemøy High is relatively poorly constrained by well data. A seismic tie between well 7216/11-1 S and 7219/9-1 is not possible due to erosion of the crest of the fault separating the Sørvestsnaget basin from the Veslemøy High (Eocene erosion seismic horizon in Fig. 9). The middle Eocene succession records a substantial westwards shift of the depocentre from the Veslemøy and Loppa Highs into the Sørvestsnaget Basin.

The Middle Eocene seismic unit is dominated by a chaotic to transparent seismic facies in the basinal lows of the Sørvestsnaget Basin. The unit onlaps the Veslemøy High–Senja Ridge structural lineament in the east. It may also be present on the Marginal High that delineates the Sørvestsnaget Basin towards the west.

The incision at the fault crest of the Eocene erosion seismic horizon (Figs 8, 9) sourced the steep, localised fans or wedges observed on the down-faulted, hanging wall block of the Sørvestsnaget Basin (Fig. 8). The age of these fans is poorly constrained since they have not been drilled. But since the fans downlap onto the lower Eocene seismic horizon and the mid Eocene seismic horizon, the Eocene erosional event is approximately mid Eocene in age.

A series of en échelon normal faults are observed throughout the Sørvestsnaget Basin (Figs 3, 9) offsetting the lower Palaeogene succession. The fault offset terminates synchronously at the mid Eocene seismic horizon, which provides an upper temporal constraint of the fault movements. This is consistent with early rift phase faulting, where minor faults are evenly distributed across the rift basin (Gawthorpe & Leeder 2000; Fig. 9). This is in contrast with the interpreted time equivalent seismic units in North-East Greenland, where only limited faulting is observed, but it can be attributed to the transtensional nature of the West Barents Sea margin. The unit thins significantly across the Marginal High where it displays local uplift-related erosion.

The faults in the Sørvestsnaget Basin are oriented

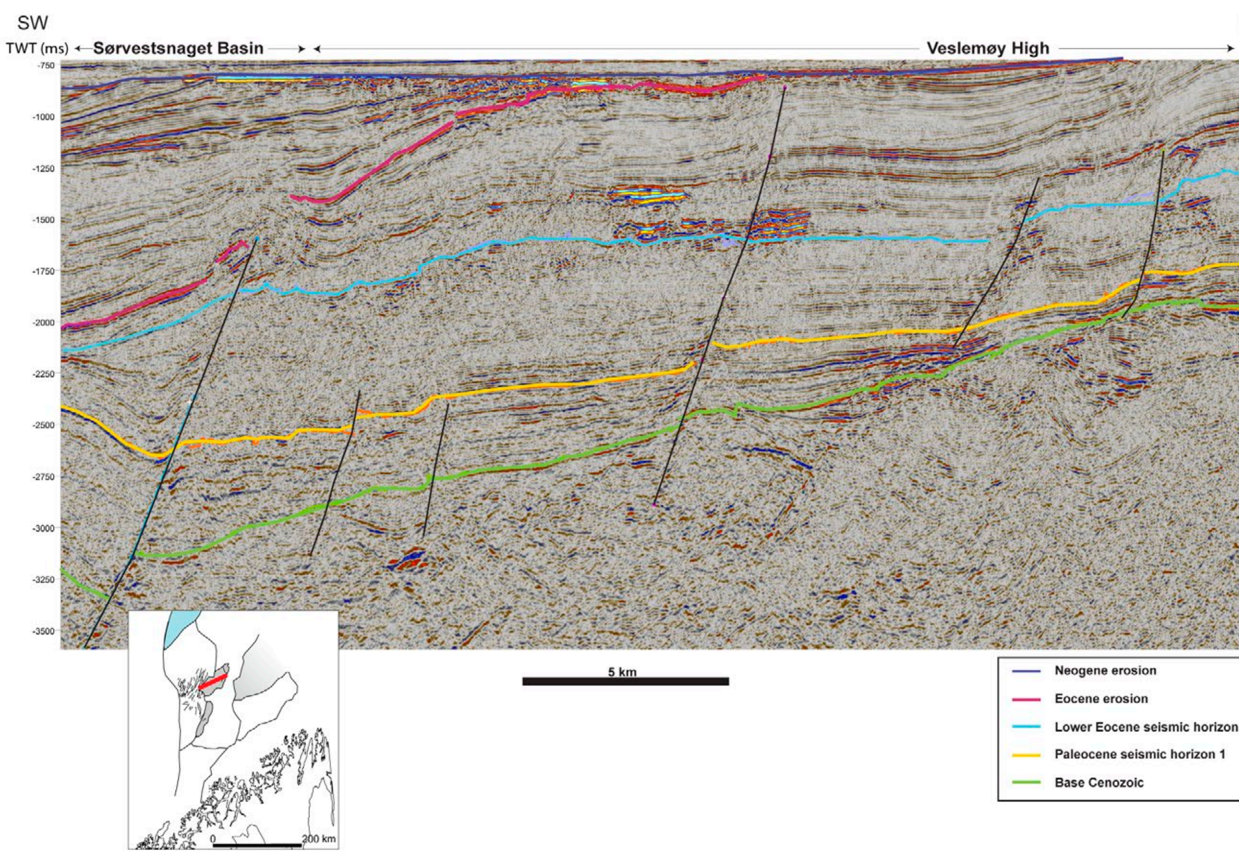

Fig. 8. Seismic example (NH9702-234) of the transition zone between the Veslemøy High and the Sørvestsnaget Basin. Note the Eocene erosion below the magenta horizon relating to footwall uplift along the western margin of the Veslemøy High. Localized wedge shaped deposits are observed west of the black fault separating the Veslemøy High to the east and the Sørvestsnaget Basin in the west. For location of inset map see Fig. 1.

N–S in the southern part of the basin and show a clockwise rotation to NNE–SSW further north (Fig. 3). The rotation roughly coincides with the transition from the Senja Ridge to the Veslemøy High (Fig.3). The Sørvestsnaget Basin was created by dextral movement along a releasing bend in the plate margin (Ryseth *et al.* 2003; Gaina *et al.* 2009). Compared to analogue models for pull-apart basins (Wu *et al.* 2009), the fault configuration of the Sørvestsnaget Basin (Fig. 3) clearly resembles the expected fault geometries of a pull-apart basin in a transverse fault system. The middle Eocene succession was deposited during the breakup of the western Barents Sea and North-East Greenland. The subsequent deepening generated deep marine conditions in the Sørvestsnaget Basin (Ryseth *et al.* 2003).

Upper Eocene seismic unit

The lower boundary is the Mid Eocene Seismic Horizon and the upper boundary is the Near Top Eocene reflection (Fig. 9). The interval is only tied to well 7216/11-1 S in the Sørvestsnaget Basin. The depocentre of this seismic unit is located in the Sørvestsnaget Basin and coincides with that of the Middle Eocene Seismic Unit. The thickest well penetration of the Eocene succession is recorded in well 7216/11-1S in the Sørvestsnaget Basin where *c.* 1000 m of Eocene sediments are present (Fig. 6). The seismic observations also show a clear westward shift in depocentre during the Eocene (Fig. 5). Seismic data indicate even larger thicknesses centrally in the Sørvestsnaget Basin compared to well 7216/11-1S, implying significant subsidence of the Sørvestsnaget Basin during the Eocene and start of drifting following continental breakup.

The seismic facies of the upper Eocene deposits predominantly displays low amplitude to chaotic reflectivity (Fig. 9). Low angle progradational to aggradational geometries are present across the basin. Downlap terminations are observed on the mid Eocene horizon and on the Marginal High (far left in Fig. 9). This indicates that the Marginal High acted as a positive bathymetric element during deposition of the upper Eocene succession. Truncation below the Near Top Eocene Seismic Horizon is observed centrally in

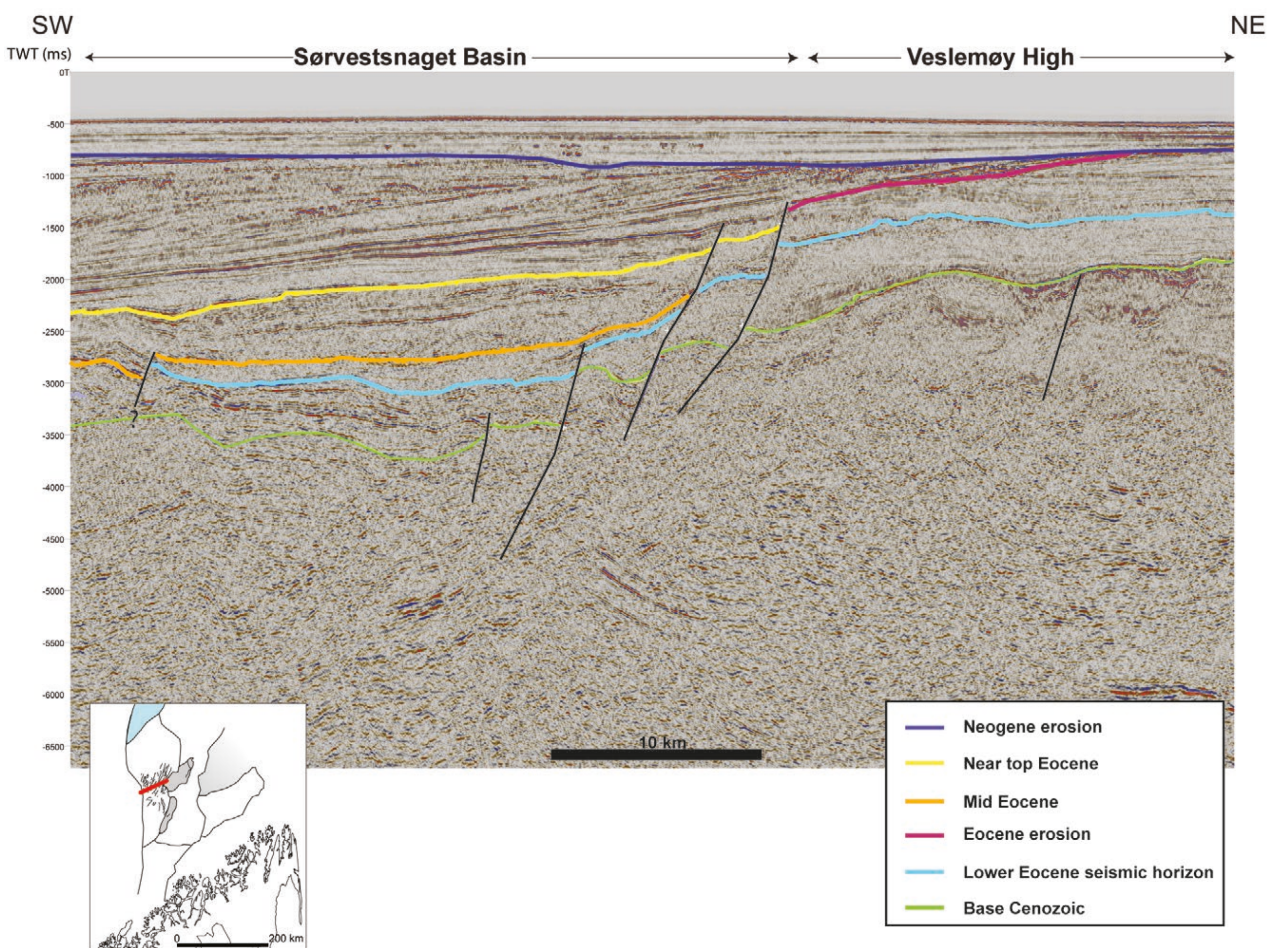

Fig. 9. Seismic transect across the Veslemøy High–Sørvestsnaget Basin transition (NH9702-234). Substantial subsidence of the basin during the Eocene is seen towards SW.

the Sørvestsnaget Basin. The incision deepens towards the Marginal High, indicating that the erosion was related to uplift of the Marginal High in Late Eocene to Early Oligocene times. The tectonic activity during the late part of the Eocene seems low compared to the preceding period, since very few faults intersect the upper Eocene interval (Fig. 9). Furthermore, the faults are located closer to the Marginal High.

The upper Eocene interval records significant changes in both thickness and lithology across the area (Fig. 6). In well 7219/9-1, it is relatively thick (*c.* 500 m) and intersected by westwards deepening, post-Palaeogene erosional incision (observed in the seismic data). This indicates that original thickness most likely exceeded 500 m. The Eocene succession in well 7117/9-1 on the Senja Ridge is less than 100 m thick, which implies that it was uplifted and acted as a positive bathymetric element during the Eocene. The uplift of the Senja Ridge coincides with uplift of the Veslemøy High immediately to the north, as observed in seismic cross sections (Fig. 8).

The petrophysical well logs indicate shale dominance in the Eocene except in the interval from *c.* 2900 to 3150 m MD in 7216/11-1S where several sand beds are recorded in log data and cores (Ryseth *et al.*, (2003). Intraformational faulting is observed towards the centre of the basin and is often associated with environments dominated by fine-grained material and relatively high sedimentation rates (Cartwright & Lonergan 1996). This is consistent with the seismic facies and lithology recorded in wells, that the depositional environment was predominantly sublittoral.

Oligocene deposits

The Oligocene succession is *c.* 100 m thick in well 7216/11-1S (Fig. 6) (Ryseth *et al.* 2003). Due to the condensation of the seismic reflections and a lack of a firm well tie, a top Oligocene horizon is not included in the study.

Oligocene deposits are only observed in the Sørvestsnaget Basin (Ryseth *et al.* 2003). The Senja Ridge, Veslemøy High and the Marginal High formed positive bathymetric elements during this period, since reflections immediately above the Near Top Eocene Seismic Horizon show onlap onto the highs in the Sørvestsnaget basin (Fig. 9). Oligocene sediments are only present in the two westernmost wells, 7216/11-1S and 7117/9-1 (Fig. 6), indicating that no Oligocene sediments were deposited east of the Sørvestsnaget Basin.

The seismic geometries indicate deposition during a tectonically quiet period during early drift. The limited tectonic activity observed during the late Eocene continued during the Oligocene. Deposition coincides with the onset of diverging absolute plate motions between Eurasia and North-East Greenland, thus marking the full evolution into passive margins along the breakup margins (Gaina *et al.* 2009).

Lofoten-Vesterålen Margin

At the Lofoten-Vesterålen margin, the conjugate to the southern North-East Greenland margin (Tsikalas *et al.* 2001), Palaeogene deposits are only preserved in the deeper parts of the basins due to post-Eocene erosion (Faerseth 2012). The erosion deepens away from the breakup axis (Bergh *et al.* 2007), as also observed on the North-East Greenland shelf (Petersen *et al.* 2015) and in the West Barents Sea area.

The Paleocene succession on the Lofoten-Vesterålen Margin is described to have prograding wedge geometries downlapping on Cretaceous sediments (Tasrianto & Escalona 2015). They are included in the Danian to upper Paleocene Tang and Tare formations which in well 6710/10-1 are composed of shales with interbedded tuffs, interpreted to be deposited in a deep marine environment formed as the result of thermal subsidence following extensive Cretaceous (and earlier) rifting events (Tsikalas *et al.* 2001; Bergh *et al.* 2007). This part of the succession resembles the pre-breakup succession on the North-East Greenland margin.

Well 6706/6-1 in the northern Vøring Basin, just south of the Lofoten-Vesterålen Margin, is reported to contain Palaeogene sandstones derived from Greenland (Norwegian Petroleum Directorate 2010). When reconstructing the plates back to a syn-breakup setting, the well site is located proximal to the area affected by uplift in North-East Greenland (Petersen *et al.* 2015), and the two margins appear to have shared sedimentary source area prior to the breakup. Continental breakup was initiated in the early Eocene (Faerseth 2012), synchronous with the other margins surrounding the Norwegian-Greenland Sea (Olesen *et al.* 2007; Gaina *et al.* 2009).

Evolution of the West Barents Sea

By integrating the information presented in the previous sections, we here present a model for the evolution of the West Barents Sea during the Palaeogene (Fig. 10). This model encompasses previous studies (e.g. Faleide *et al.* 1993; Richardsen *et al.*1991; Ryseth *et al.* 2003), supplemented with interpretations of features important for the correlation to North-East Greenland. The described seismic units are associated with the three main phases of the breakup history: Pre-breakup units (Lower Paleocene, Lower–upper Paleocene), breakup units (Lower Eocene, Middle Eocene) and (early) drift units (Upper Eocene, Oligocene). Fig. 10 displays the large-scale geometries of the sediments deposited during these three phases.

The geometry of the lower Paleocene succession suggests deposition during a tectonically relatively quiet period following a period of non-deposition along the western Barents Sea margin (Dalland *et al.* 1988; Knutsen & Vorren 1991; Gaina *et al.* 2009). The Loppa High was a positive topographic element during the Paleocene and possibly acted as a local source area since prograding clinoforms of this age are observed on and west of the high (Figs 7, 10). However, progradation was somewhat limited and the larger parts of the adjacent Tromsø Basin are characterized by sub-horizontal reflections suggesting sublittoral deposition. Tsikalas *et al.* (2005) report some Late Cretaceous–Early Paleocene deformation along the margin, but the effects on deposition were limited. Evidence of fault movements that predate the onset of continental breakup includes footwall uplift of the Senja Ridge and the Veslemøy High, recorded by the onlap of the Paleocene reflectors (Fig. 10A).

Palaeogene normal faulting is observed both east and west of the Sørvestsnaget Basin. The seismic data suggest that faulting started along the eastern margin of the basin and then migrated westward towards the margin of the shelf, causing westward migration of the depocentre (Fig. 5). The westward translation of faulting culminates in the De Geer Mega Shear Zone that separates the Sørvestsnaget Basin from the Lofoten Basin (Fig. 3). The Marginal High was uplifted during this fault culmination, indicated by onlap onto the high and erosion of its top. The distribution and orientation of the faults in the Sørvestsnaget Basin are consistent with models of transtensional pull-apart basins where en échelon soft linked faults outline the basin (Wu *et al.* 2009).

The seismic data show evidence of prograding clinoforms building out from the east into structural lows and across highs along the West Barents Sea margin during the Palaeogene (Fig. 10). The thickness

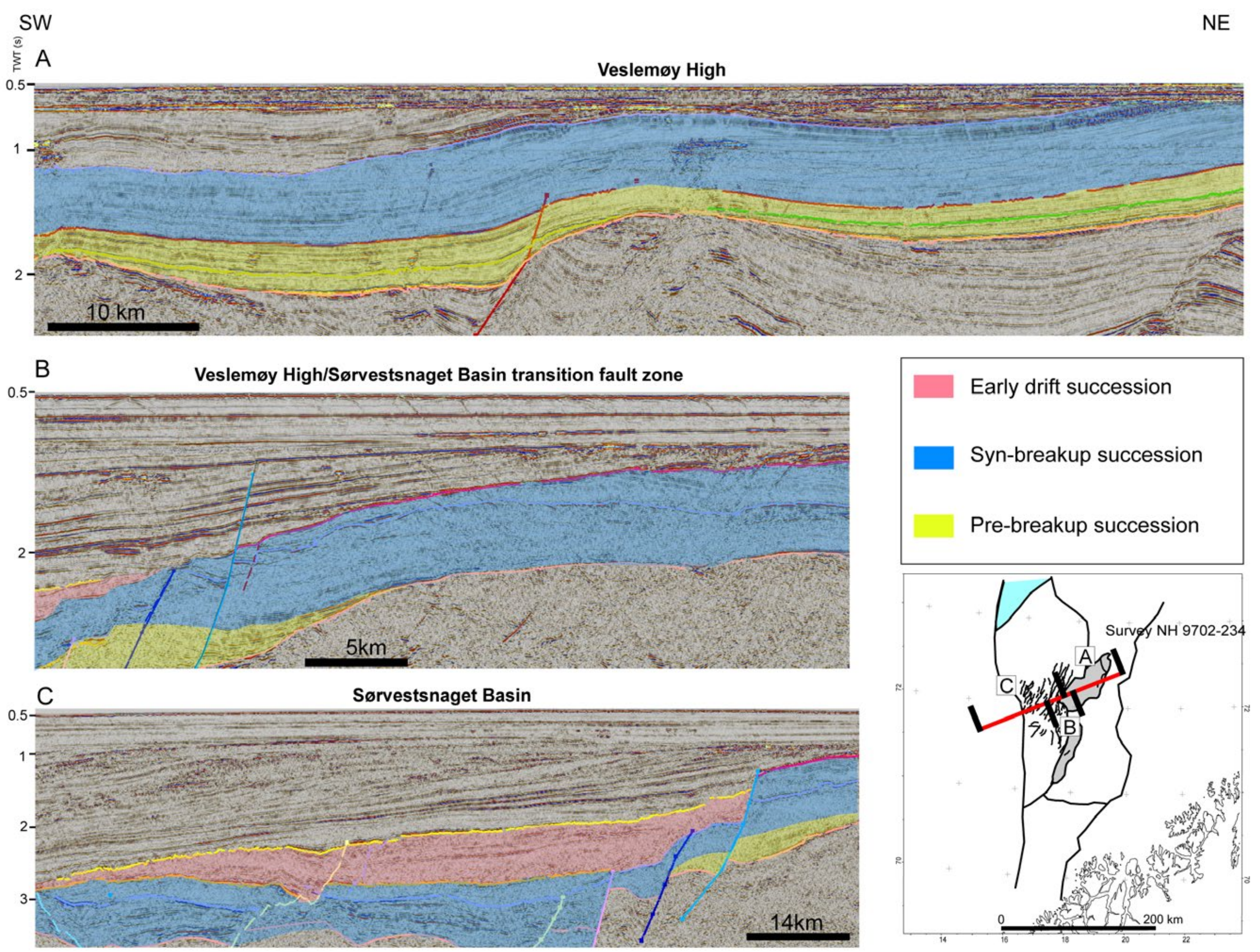

Fig. 10. Three seismic examples from the West Barents Sea, showing the subdivision of the Palaeogene succession. See text for detailed description. For location of inset map see Fig. 1.

variations observed between the Loppa High, Senja Ridge and Sørvestsnaget Basin further illustrate the evolution before, during and after breakup (Fig. 5). The pre-breakup succession, represented by the Paleocene interval, shows relatively homogenous thicknesses across the margin, whereas the Eocene breakup succession displays significant thickness changes as this interval is condensed across the Senja Ridge. The thicknesses of the early drift sequence, as represented by the upper Eocene to Oligocene succession, are significantly smaller than those of the underlying intervals. This indicates condensation of the early drift succession on the continental margin and a westward shift of the depocentre into the Lofoten Basin.

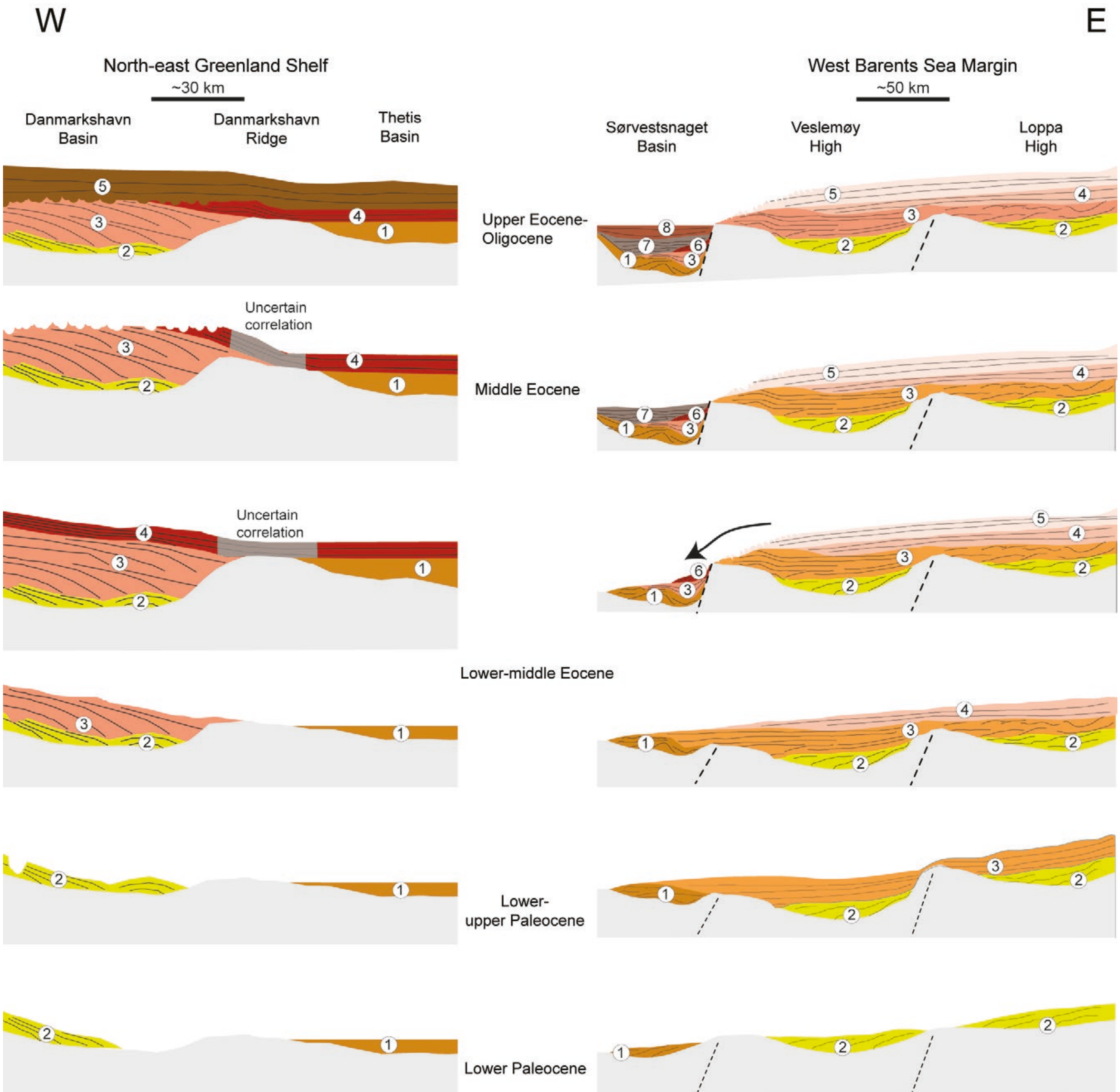

Fig. 11. Simplified correlation across the conjugate margins based on similarities in depositional geometries. The pre-breakup deposits (Lower–Upper Paleocene) are characterised by low angle clinoforms filling out basinal lows. The syn-breakup succession (Eocene) displays steeper clinoforms than below and a more pronounced progradation across structural highs on both sides. The early drift interval (Middle Eocene–Oligocene) of the conjugate margins is dominated by sub-horisontal stratal geometries, with a large extent in the North-East Greenland area, whereas the deposition is centred in the Sørvestsnaget Basin and in the Lofoten Basin further west (not displayed) on the West Barents Sea margin. Colours are solely used to distinguish individual seismic units and hold no other significance. Numbering refers to the chronostratigraphic chart presented in Fig. 12.

Conjugate margin seismic correlation

By combining the information from the seismic stratal geometries with the temporal constraints derived from wells drilled in the West Barents Sea, as well as the timing of volcanism in North-East Greenland, we suggest the correlation scheme shown in Fig. 11. The chronostratigraphic correlation of the seismic units of the North-East Greenland and the Western Barents Sea margins is based on the described similarities of stratal stackning patterns at the two margins. The common thermal and plate tectonic history during continental breakup forms the framework for the correlation. All available stratigraphic information is utilised to date the seismic sections. (Faleide *et al.* 1993; Faleide *et al.* 1996; Ryseth *et al.* 2003). Significant structural differences exist between the two margins, as the northwest Eurasian margin is dominated by complex compressional, strike-slip and extensional tectonics (Saettem *et al.* 1994; Tsikalas *et al.* 2002), whereas the North-East Greenland margin is mostly dominated by extensional tectonics during the Palaeogene breakup (Petersen *et al.* 2015). This is primarily observed as a higher frequency of faulting during the pre-breakup and syn-breakup phases on the West Barents Sea margin. This is most likely caused by the transverse motions along the De Geer Mega Shear zone, where true passive margin development occurred later compared to North-East Greenland.

The lower Palaeogene seismic stratal geometries are dominated by infill between structural highs that formed positive bathymetrical elements on both margins (Figs 4A, 10A–C). In the West Barents Sea area, the rotated fault blocks of the Veslemøy High and Senja Ridge are positive structural elements (Fig. 5). On the North-East Greenland margin the Danmarkshavn Ridge separates depositional areas from the incipient breakup zone. The Danmarkshavn Ridge has a position similar to that of the rotated fault blocks on the West Barents Sea Margin (Figs 4A,B, 5, 11). Both margins show evidence of low angle prograding to sub-parallel infill to be focused in the lows, which is consistent with deposition on flooded end-Mesozoic inherited topography. Relatively low gradients in both the basin and hinterland are expected in this setting (Hamann *et al.* 2005; Worsley 2008; Petersen *et al.* 2015). Deposition is interpreted to take place in the tectonically relatively quiet period following the prolonged Late Palaeozoic–Mesozoic rifting that occurred in the region prior to the opening of the North Atlantic (Doré 1991). Therefore, the succession is interpreted to predate continental breakup, and a Paleocene age for the pre-breakup package on the North-East Greenland shelf is suggested by correlation with the West Barents Sea margin (Fig. 4A, marked in yellow, and Figs 11, 12).

A distinct increase in the angle and amplitude of prograding clinoforms mark the onset of the continental breakup, most likely caused by thermal heating in relation to the break-up volcanism (recorded in the lower Eocene deposits on the conjugate margins) (Figs 4B, 10B, 11). Uplift of the proximal areas of the margins and subsidence towards the central zone of breakup caused an overall increase in depositional gradient and sediment influx onto the shelf areas, thus marking a significant change which can be dated to near the Paleocene–Eocene transition in the Barents Sea (Fig. 9). A similar age for the onset of large scale progradation is suggested for North-East Greenland. The progradtional succession has an erosive upper boundary which we interpret as the effect of volcanic induced thermal doming (Petersen *et al.* 2015), deepening towards the south and west (Fig. 4A, B). We suggest an earliest Eocene age for the onset of the deposition of the syn-breakup package in North-East Greenland (Fig. 4A) (Petersen *et al.* 2015).

Plane-parallel seismic facies tops the Palaeogene succession on both margins, suggesting deposition in a relatively quiet, deep marine setting (Figs 4C, 10C, 11), as confirmed in well bores penetrating this level on the Barents Sea margin. The well data indicate a Late Eocene to Oligocene age for the plane-parallel packages (Fig. 6) (Ryseth *et al.* 2003). Similar ages are suggested for the seismic units included in the early drift succession on the North-East Greenland shelf. The age of the upper boundary of the succession is associated with some uncertainty.

Chronostratigraphic implications

A pronounced symmetry of the seismic geometries is observed across the North-East Greenland and West Barents Sea margins, and we propose that this symmetry reflects a genetic, temporal relationship of the conjugate margin set (Fig. 12). The two margins show a comparable stacking of seismic facies. The locus of the sedimentation shifted synchronously towards the breakup axis on both the West Barents Sea and North-East Greenland margins, most pronounced on the West Barents Sea margin (Fig. 12). Figure 5 shows that pre-breakup deposition is constricted by basinal highs on both margins. On the Greenland side, the Danmarkshavn Ridge forms the barrier, whereas the footwall uplift along the west margin of the Veslemøy High forms the barrier in the West Barents Sea area (Fig. 1, pre-breakup interval on Fig. 12).

During the volcanically active breakup phase, pronounced progradational events shifted the depocentres of both margins further towards the central axis of breakup (Figs 11, 12). This is also observed in the thickness distribution of the sediments deposited during breakup (Fig. 5). Basinal highs are overstepped and sediments accumulate in the basins near the breakup zone. The breakup phase was dominated by an increase in both accommodation space and sediment supply as basins were formed near the breakup axis and the hinterland produced more sediment due to an increased gradient of the depositional system (Fig. 12). In the Sørvestsnaget Basin on the Barents Sea margin, extensive normal faulting occurred during this period (Fig. 9) as a result of pull-apart tectonism, whereas the southern North-East Greenland Margin was less tectonically deformed (Fig. 4). Tectonism that influenced the depositional fairways are however observed in the Eurekan region, most likely including the Wandel Sea (Petersen *et al.* 2016).

Following breakup, early drift deposition is dominated by a relatively homogenous distribution of sediments across both margins and further basinward migration of the depocentres. Post-breakup erosion intersects the Palaeogene succession on both margins, hampering any palaeogeographic interpretation away from the central axis of breakup (Fig. 5). In the West Barents Sea, the Veslemøy High–Senja Ridge area is apparently uplifted during this phase (Figs 11, 12), and hence deposition is restricted to the Sørvestsnaget Basin, but other studies have shown that deposition during early drifting also occurred further to the west in the Lofoten Basin (Ryseth *et al.* 2003). The distribution and limited lateral thickness variations are consistent with this succession representing deposition during a relatively quiet period of thermally related, large scale subsidence following the heating of the margins during the breakup volcanism. The transition to early drift deposition is observed on both margins as aggradational geometries with onlaps on the structural highs (Fig. 12). Evidence of a common tectonic history is also found in the form of a soft-linked, right-lateral transfer zone that correlates between Lofoten-Vesterålen and North-East Greenland (Faerseth 2012; Petersen *et al.* 2015).

Conclusions

The seismic units identified on the North-East Greenland shelf and in the West Barents Sea have been correlated on the basis of their stratal geometries and their relation to plate tectonic and volcanic events, thus

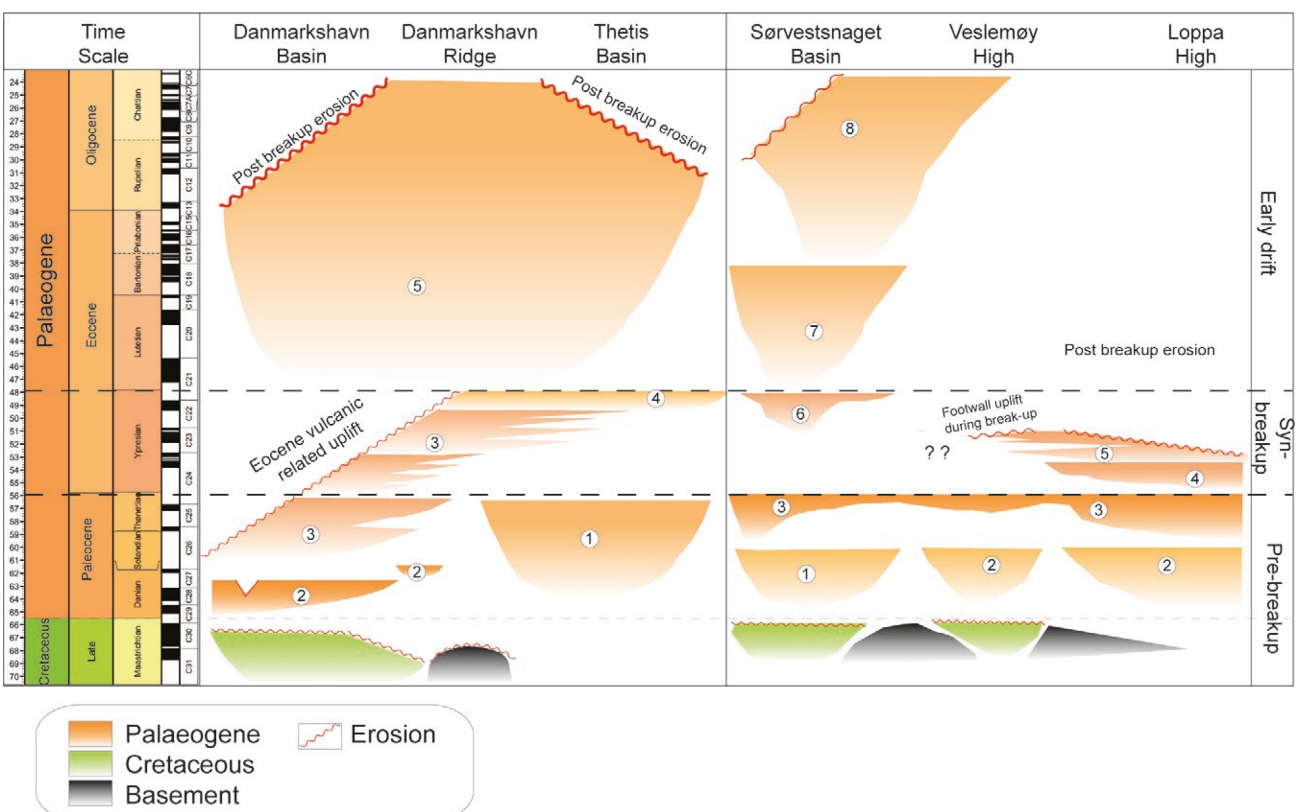

Fig. 12. Simplified chronostratigraphic chart correlating the individual depositional units identified at both conjugate margins. The absolute ages are associated with some uncertainty. Numbers refer to the seismic units shown in Fig. 11.

facilitating a more robust dating of the Palaeogene succession on the North-East Greenland shelf.

A comparison with the Lofoten-Vesterålen Margin revealed depositional geometries of the Tang and Tare Formations that correlate well with the pre-breakup succession in North-East Greenland. Paleocene sandstones in Norwegian well 6706/6-1 derived from North-East Greenland suggest a linkage between the two areas prior to and potentially during the time of volcanic uplift (Norwegian Petroleum Directorate 2010; Petersen *et al.* 2015).

A simplified correlation scheme of the Palaeogene interval between the North-East Greenland shelf and the West Barents Sea margin is proposed (Fig. 12). The scheme is based on the subdivision of the Palaeogene into three main packages. The pre-breakup, syn-breakup and early drift successions are well described and dated in the West Barents Sea. In contrast, the Palaeogene succession on the North-East Greenland margin has previously only been assigned to seismic megasequences (Hamann *et al.* 2005; Tsikalas *et al.* 2005). Correlating individual units across the continental breakup zone and relating them to the large-scale plate tectonics lowers the uncertainty of the dating of Palaeogene seismic units offshore North-East Greenland.

The pre-breakup succession of the North-East Greenland shelf consists of low-angle clinoforms and basin floor fans and is dated as Paleocene, and therefore predates the continental breakup (Figs 11, 12). The North-East Greenland shelf was relatively tectonically quiet during this period, where deposition was mostly restricted to the Danmarkshavn Basin. In contrast, the West Barents Sea margin underwent significant transtensional tectonism during this period.

The Eocene breakup interval displays pronounced progradation across both the North-East Greenland and West Barents Sea margins in response to an increased gradient of the depositional system, thus increasing sediment input into the basins. Structurally, the breakup phase of the North-East Greenland succession is relatively quiet. The Danmarkshavn Ridge is overstepped by prograding clinoforms, and seismic reflections are correlated into the Thetis basin. A similar pattern is observed in the West Barents Sea area, where structural highs are overstepped, and the depositional system display progradation and lateral shift of depocentre towards the breakup axis (Figs 11, 12). However, in contrast to the North-East Greenland margin, the Barents Sea margin is associated with a significant amount of normal faulting in the Sørvestsnaget Basin due to its transtensional nature. The Late Eocene–Oligocene early drift phase was dominated by deposition below wave base, with hemipelagic sedimentation over a flooded continental margin. Tectonism was limited during this period, with only minor evidence of fault activity at the margins. Thermal cooling was the main process creating the accommodation space and generated seismic units of relatively homogenous thicknesses.

Acknowledgements

The authors wish to thank DONG Energy and the KANUMAS partners (BP, Chevron, Exxon, JOGMEG, Shell and Statoil) for providing the data and significant financial support for this study. Several people at conferences have commented on the current work, which helped to improve this manuscript. Furthermore, the manuscript benefitted greatly from the input of the reviewers.

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